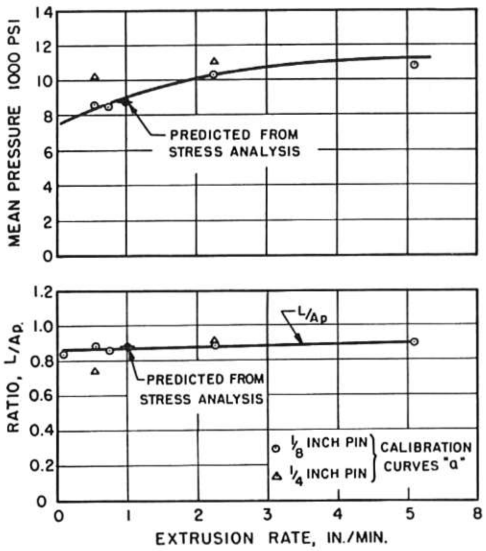

Fig. 8 Measured and Predicted Mean Pressure as a Function of Extrusion Rate
(Distance between pressure gages and die is 0.4 in.)

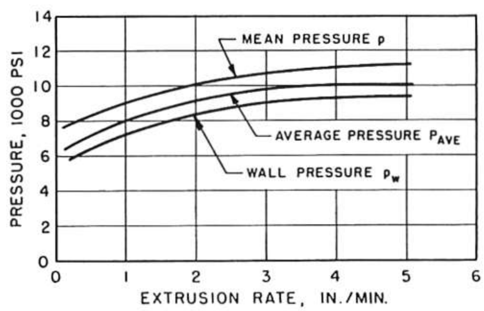

Fig. 9 Comparison Between Mean Pressure, Wall Pressure, and Average Pressure as Functions of Extrusion Time
(Distance between pressure gages and die is 0.4 in.)

Conclusions

1 The mean pressure within an extrusion billet can be determined experimentally with a pressure gage.

2 The size of the gage pins inserted in the wall of the extrusion cylinder has a definite influence on the accuracy with which the mean pressures can be found, the smaller pins giving more accurate values.

3 The same wall pressure was measured with different-sized gage pins and was found to agree with the calculated values.

4 The mean pressures found experimentally agreed with those predicted from a stress analysis based on the experimental flow patterns.

5 The applied load and wall pressure as well as the mean pressure were found to increase linearly with increasing extrusion rates.

Acknowledgments

The author wishes to thank Prof. E. G. Thomsen of the Division of Mechanical Engineering at the University of California at Berkeley, for his valuable aid and numerous constructive suggestions. He also wishes to thank the College of Engineering for the use of its facilities and providing research grants for the investigation.

Discussion

E. V. Crane.[8] This paper is a thorough presentation of the application and calibration of a strain-gage pressure pickup, with experimental data from the room-temperature extrusion of lead, to illustrate use of the device.

The data presented in chart form are interesting for purposes of interpretation. The shape of the curves obtained, illustrating change of pressure with increasing speed of extrusion, checks with experience in other thermoplastic metal working operations.

Since our knowledge of physical behavior of metals in their thermoplastic range is rather inadequate, the author's data and method together with cross-referenced work of Prof. E. G. Thomsen promise future advances. May we review the situation briefly in order to draw a further interpretation and raise a question for possible continued research?

Rubber, in an elastic noncrystalline state, acted like a hydraulic fluid in transmitting pressure from the direction of the applied force to the perpendicular direction of the measuring instrument in so far as could be detected in the data shown in Figs. 3 and 4 of the paper.

Lead, a metal, did not so act as shown in Figs. 6 and 7. Its interatomic bonds are still too potent to permit the fluid behavior which it would have at a higher temperature (above its melting point). Neither does it have the characteristics of the crystalline state which exists at lower temperatures where metal is elastic up to stresses described as elastic limit and yield point.

The valuable range is that in which most of the mass-production utility of plastically worked metals may be realized. In that range we have the phenomena of slip-plane movement, work-hardening, and increasing yield point. Poisson's ratio enters into directional relationships in some way which does not seem too clear as we pass from the elastic state to crystoplastic "cold" flow.

The recrystallization temperature range of the annealing process, varying with time and prior working, separates crystoplastic behavior from thermoplastic behavior. This is the technical boundary between the loose trade terms of "cold" working and "hot" working, forging, etc.

In the thermoplastic state both experimental work and observation shows that work hardening takes place even though an annealing readjustment, dependent upon the thermal energy of the atoms, is tending to return interatomic forces to "unstrained" balance. The directional effect or "polarity" of such forces may enter into our present problem. Time, temperature, and space lattice relationships are all part of it.

Lead is in its thermoplastic range at room temperatures, a point which the writer believes should be emphasized, for its implications should influence those who would make practical application of the valuable work in this paper.

Figs. 6 and 7 of the paper combine the results of thermoplastic behavior of lead with dimensional characteristics of the test apparatus.

Curve *a* rises with some of the characteristics of the stress-strain curve of the crystoplastic state but without a defined elastic limit or yield point. The lead billet deforms thermoplastically until it fits and fills the test chamber. Then the stress-strain relation expressed by curve *a* parallels the rubber calibration curve as the applied force expands the container elastically. It is higher, however, showing the need for more applied "axial" force to produce the "radial" force and movement detected by the SR-4 strain gage when calibrated with rubber.

Here we have characteristics of thermoplastic pressure-tem-

[8] Chief Engineer, E. W. Bliss Company, Canton, Ohio; Chairman, ASME Research Subcommittee on Plastic Working of Metals. Mem. ASME.

perature directional relationships. It is distinctly neither a hydraulic fluid relationship nor a crystalline elastic one. There is some space lattice angular transmission problem as yet ill defined in the art.

The return curve *b* in Figs. 6 and 7 shows that the test develops a prestressed state in which the container remains under elastic stress and the lead holds at a temporary "solid" yield point which might be interpreted at about 1600 psi, from the rubber calibration curve. Actually, it is higher owing to the loss of pressure in the right-angle transmission through lead. This higher apparent yield stress might be averaged at about 2800 psi by extending the curves *a* until they intersect the zero stress scale.

The repetitive curves *c-d* show in an interesting manner the combined effect of container elastic stress with the thermoplastic characteristics of the lead. As direction is reversed the container stress alternately opposes and aids applied load, resulting in the "hysteresis" loop effect. The residual strain reading of about 45 microinches on the gage would probably "creep" back to zero with sufficient time, dependent upon the thermoplastic temperature-creep characteristics of lead.

May we argue that curve *c*, extended back to zero in Figs. 6 and 7, represents a proper calibration between radial gage reading and the axial stress in the lead near the gage, and that this calibration may be applied to the actual working conditions during extrusion? If this is proper, as it seems to be, then the wall pressure may be replotted to the axial calibration by proportion to

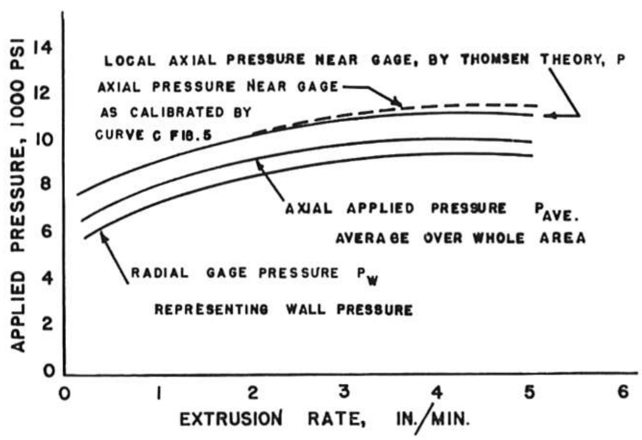

Fig. 10 Author's Fig. 9 With Dotted Curve Added

(The local pressure on "trapped" lead in corner by gage is properly higher than average of pressure over whole area, including orifice. Does approximately 20 per cent difference between radial and axial stress in lead in that area represent a nonfluid directional ratio for thermoplastic lead, on the order of Poisson's ratio for crystalline state?)

the rubber calibration line. This was done in Fig. 10, herewith, and the resultant dotted curve checks clearly with Professor Thomsen's theoretical derivation of the local pressure in that area.

The fact that the applied pressure (axial) is lower is logical because it is the average of pressure applied over the whole area compared with a high local pressure in a trapped corner. The difference merely emphasizes the high "viscosity" or interatomic "internal friction" of thermoplastic lead. (Local axial pressure in the orifice is obviously below the average.)

The radial stress in the semistatic corner metal near the gage appears to be about 20 per cent less than the axial stress, at the different extrusion speeds. May we theorize that this traces to some remaining directional difference in interatomic forces in the thermoplastic state? Does the 20 per cent figure represent something akin to Poisson's ratio for thermoplastic lead? Does it vary with temperature? These may be proper questions for further research into thermoplastic flow properties of metals.

Author's Closure

The author is indebted to Mr. Crane for his valuable comments. The question is raised whether curve *c* rather than curve *a* in Figs. 6 and 7 should be the proper calibration curve of the pressure gage. Computations on the stress analysis of tubular lead extrusions which have been done since the presentation of this paper showed an agreement within approximately 5 per cent between predicted and measured wall pressure when curve *a* in Fig. 6 is used.

The range of wall pressures for lead extrusion is between 8500 and 10,000 psi. A comparison of the microinch readings of curves *a* and *c* for any given stress level within the foregoing range shows a difference which is so small one may consider it to be almost within the realm of experimental error. The dotted curve of Fig. 10 shows the small change involved when either curve *a* or *c* is used in that range.

The discusser's comparison of curve *a* in Figs. 6 and 7 to the stress-strain curve is very interesting. If curves *b* and *c* are similar to the unloading and reloading curves of a stress-strain diagram after the plastic range has been reached, then the analogy could be carried further, namely, that curve *a* is representative of wall pressures during the initial extrusion run but curve *c* gives wall pressures for runs which take place after interruption and subsequent reloading.

The suggested study of the relationship between average pressure and radial wall pressure as a function of temperature should yield some very interesting and pertinent data; however, the presence of thermal stresses in the pressure gages would necessitate a complete change of the present design.